TITLE: PROCESS FOR MEASURING THE SPEED OF AN INDUCTION MOTOR FROM NULL APPLIED FREQUENCY STATUS

SPECIFICATION

Object of the present invention is a process for measuring the speed of an induction motor when the applied frequency is null in a control of the Sensorless type.

The application type to which the process is usefully applied regards all uses in which the load is able to turn the motor moving meanwhile the control is released.

The terms "control is released" mean the zeroing of every current in stator phases. The main (but not only) application to which reference will be made is the traction of an electric vehicle on steep paths: abandoning the vehicle on a ramp, with released accelerator, a torque is produced that tends to drag the vehicle along the descent. When a vehicle or car is dealt with, this will mean the one handled by the motor.

The definition null applied frequency means any situation in which a non-null triad of direct currents is applied to stator phases to produce a non-null current phasor (herein below called stationing phasor or stationing current) whose spatial orientation is fixed and could be any one within the electric 360° range.

Sensorless control methods are known for induction motors based on the estimation of magnetic flux components.

It is also known that, under the null applied frequency status, said methods fail due to the zeroing of electromotive forces in stator phases from whose measure the flux components are obtained.

The difficulties in measuring the flux with null applied frequency can be ignored if a speed measure is available as an alternative. The herein below described idea is a process for measuring the vehicle speed starting from the null applied frequency status.

The null applied frequency status supplies in the motor a torque that opposes the motion (stationing torque *Tstand*). This stationing torque will be useful for preventing the free vehicle rotation once having ended any deceleration manoeuvre towards the vehicle stop. Invariably, zero deceleration operations of the vehicle will end with the application of a stationing phasor. If the vehicle is on a descent path, the stationing phasor will not completely stop it, but will brake its descent according to the herein below described mode. By providing the general expression of the Torque (2.9) in case of null applied frequency, for *Tstand* an expression is found whose qualitative behaviour (as function of electric motor speed ωr and for two different widths of the stationing phasor *Idc*), is shown on the curve in FIG. 2 and refers to a Motor with Rated Power $Pn = 1250W$, $Vphase=16Veff$, a corner frequency $fc=75\ Hz$ and Rotor Time Constant $Tr = 62\ msec$.

It can be demonstrated, and it is also pointed out in FIG. 2, that at low speeds the stationing torque is proportional to the product between speed (ωr) and square of stationing phasor width.

It can further be seen that, for a load torque less than *Tsmax* (maximum stationing torque), the vehicle will be braked and its descent will occur at a low and controlled speed (it can be demonstrated that it will be $\omega r < 1/Tr$: in the example shown, $\omega r < 1/Tr = 2\pi 2.6Hz$).

If the dragging torque towards the descent exceeded *Tsmax*, the working point would go into the torque collapsed range with consequent uncontrolled vehicle acceleration along the descent.

If there is an Encoder on the motor shaft, this difficulty is easily solved by increasing the control frequency and limiting the slip in the motor at values that are able to guarantee everywhere the production of the maximum torque.

In a Sensorless control, it is rather obvious to use a management of the feedforward type (i.e open loop) for the stationing torque: it will be convenient to apply an high stationing phasor width (at least as much high as the motor saturates), in order to minimise the risk the load exceeds the maximum torque (*Tsmax*).

Since, under operating conditions, the vehicle will mainly travel on plane courses and with partial loads, the application of high stationing currents will bring about very high energy wastes as inconvenience.

It must be added that, due to the incapability of measuring the magnetic flux in the machine, it will not be possible to estimate the actual stationing torque that would allow cancelling the currents if superfluous.

Object of the present invention is therefore providing a process for deciding whether the stationing current phasor is useful and adequate. An intervention mode will then be discussed in one case or the other.

This object is fully obtained in the process for measuring the motor speed starting from an applied null frequency status, object of the present invention, that is characterised by what is included in the below listed claims and in particular in that it allows activating a motor speed monitoring function by overlapping in stator phases a particular sampling signal (a step transition of the stationing phasor) and the measure of produced effects.

The process will now be shown, merely as a non-limiting example, with reference to the enclosed drawings, in which:

- FIG.1 shows a particular configuration of the applied null frequency status, characterised by injecting a current *idc* in phase *a* and by extracting two currents *idc/2* from phases *b* and *c*.

- FIG. 2 shows the behaviour of the stationing torque *Tstand* depending on motor speed ωr and when the stationing phasor width (*idc*) changes. The curve refers to a simulation for a motor with *Pn=1250W Vphase=16Vac fc=75Hz p=2 Tr=62msec.*

- FIG. 3 shows the effects of a double step transition of the stationing current phasor (*ids=idc* from 0 to 50Adc and afterwards to 100Adc) on quadrature voltage (*vqs*); it is the result of a simulation involving the same motor as above, rotating at an electric speed $\omega r=100rd/sec$.

- FIG. 4 shows the effects of a double step transition of the stationing current phasor (*ids=idc* from 0 to 50Adc and afterwards to 100Adc) on quadrature voltage (*vqs*); it is the result of a simulation involving the same motor as above, rotating at an electric speed $\omega r=-100rd/sec$.

- FIG. 5 shows the effects of a double step transition of the stationing current phasor (*ids=idc* from 0 to 50Adc and afterwards to 100Adc) on quadrature voltage (*vqs*); it is the result of a simulation involving the same motor as above, rotating at an electric speed $\omega r=400rd/sec$.

- FIG. 6 shows the oscilloscope response of a real motor (*Pn=1250W* wound for *Vfase=16Vac fc=75Hz* and rotating at a speed of $\omega r=-100rd/sec$) at a step transition of *idc* from *100Adc* to *0*; the upper trace is *vb-vc (2V/div)*; the lower trace is the stimulus and stationing current *ias=idc (50 A/div)*.

- FIG. 7 shows the response of the same motor in FIG. 6 (rotating at a speed of $\omega r=100rd/sec$) at a step transition of *idc* from *100Adc* to *0*.

- FIG. 8 shows the response of the same motor in FIG. 6 (rotating at a speed of $\omega r=-240rd/sec$) at the step transition of *idc* from *100Adc* to *0*.

The above process must be justified at theoretical level starting from the general dynamic model for an induction motor (from 2.1 to 2.9).

$\varphi qs=L_S\, iqs+L_m\, iQs$ (2.1)

$\varphi ds=L_S\, ids+L_m\, iDs$ (2.2)

$\varphi Qs=L_R\, iQs+L_m\, iqs$ (2.3)

$\varphi Ds=L_R\, iDs+L_m\, ids$ (2.4)

$vqs=R_S\, iqs+ d/dt\, \varphi qs+\omega\, \varphi ds$ (2.5)

$vds=R_S\, ids+ d/dt\, \varphi ds- \omega\, \varphi qs$ (2.6)

$0=R_R\, iQs+ d/dt\, \varphi Qs+ \omega_R\, \varphi Ds$ (2.7)

$0=R_R\, iDs+ d/dt\, \varphi Ds- \omega_R\, \varphi Qs$ (2.8)

$$C_m=\frac{3}{2}p(iqs\,\varphi ds- ids\,\varphi qs) \quad (2.9)$$

Where:

φqs, φds: stator flux components

φQs, φDs: rotor flux components

iqs, ids: stator current components

iQs, iDs: rotor current components

vqs, vds: stator voltage components

ω: electric rotation angular speed of the reference system with respect to the stator

ω_R: electric rotation angular speed of the reference system with respect to the rotor ($\omega_R = \omega - \omega r$), with ωr electric rotor angular speed

ωr: (electric) rotor angular speed $\omega r = p\Omega r$

Ωr: rotor shaft speed

p: poles pair number

Ls: stator inductance

Rs: stator resistance

Lm: magnetization inductance

Lr: rotor inductance

Rr: rotor resistance

Tr: rotor time constant *Lr/Rr*

(2.9) is the general expression of the instantaneous torque developed by the motor.

For an obvious analysis simplification, and without affecting its generality, reference has been made to the equivalent two-phase model of the three-phase motor, which is obtained through the well-known Clarke transform (3.1, 3.2).

$$\begin{bmatrix} iqs \\ ids \end{bmatrix} = \boldsymbol{D} \cdot \begin{bmatrix} ias \\ ibs \end{bmatrix} \quad \text{With} \quad \boldsymbol{D} = \begin{bmatrix} \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} \\ 1 & 0 \end{bmatrix} \qquad (3.1)$$

and vice versa

$$\begin{bmatrix} ias \\ ibs \end{bmatrix} = \boldsymbol{D}^{-1} \begin{bmatrix} iqs \\ ids \end{bmatrix} \quad \text{With} \quad \boldsymbol{D}^{-1} = \begin{bmatrix} 0 & 1 \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix} \qquad (3.2)$$

Where:

iqs, ids: quadrature and direct components of the stator current phasor in the equivalent two-phase system whose axis *ds* is along the *as* direction.

ias, ibs: currents in phases *as* and *bs* of the three-phase motor.

For our purposes, it is interesting to note how the general dynamic representation (from 2.1 to 2.8) is modified when applying a stator current

phasor fixed in space. To simplify the analysis, without affecting its generality, such phasor will be identified with a three-phase triad composed of a current *idc* entering phase *a* and two currents *idc/2* going out of phases *b* and *c* (FIG. 1). Such current (*idc*) will be considered time depending.

By applying the Clarke transforming formulae (3.1) to the thereby defined triad, the equivalent two-phase model components are obtained.

$ids = idc$

$iqs = 0$

By replacing *iqs* and *ids* with their values, the general dynamic model (from 2.1 to 2.8) for the null frequency status ($\omega = 0$) is simplified into:

$$\varphi qs = L_m\, iQs \qquad (4.1)$$

$$\varphi ds = L_S\, ids + L_m\, iDs \qquad (4.2)$$

$$\varphi Qs = L_R\, iQs \qquad (4.3)$$

$$\varphi Ds = L_R\, iDs + L_m\, ids \qquad (4.4)$$

$$vqs = d/dt\ \varphi qs \qquad (4.5)$$

$$vds = R_S\, ids + d/dt\ \varphi ds \qquad (4.6)$$

$$0 = R_R\, iQs + d/dt\ \varphi Qs - \omega r\ \varphi Ds \qquad (4.7)$$

$$0 = R_R\, iDs + d/dt\ \varphi Ds + \omega r\ \varphi Qs \qquad (4.8)$$

$$C_m = -\frac{3}{2} p\ ids\ \varphi qs \qquad (4.9)$$

By processing the above model (from 4.1 to 4.8), a linear second-order differential equation is obtained, that expresses the functional dependency of quadrature voltage *(vqs)* from current *ids* in direct phase *(ids = idc)* with *iqs* = *0:*

$$\frac{1}{\omega r}\frac{dvqs}{dt} + \frac{2}{\omega r Tr} vqs + \frac{1 + \omega r^2 Tr^2}{\omega r Tr^2}\left[\varphi qs(0+) + \int_0^t vqs(t)dt\right] = \frac{RrLm^2}{Lr^2} ids \qquad (5)$$

To complete, the similar functional relationship *vds=f(ids)* could be determined. Its analysis however will be more complex and worsely readable. Therefore, only relationship (5) will be studied.

Transforming relationship (5) from zero-state, namely from null initial conditions $(vqs(0+)=0,\ \varphi qs(0+)=0)$, the representation (6) in the Laplace domain is obtained:

$$Vqs(s)=\frac{\omega rLm^{2}}{RrTr^{2}}\frac{s}{(s+1/Tr)^{2}+\omega r^{2}}Ids(s) \qquad (6)$$

Relationship (6) manages the reply (*vqs*) of our motor to the application of any current *ids(t)* (provided that it is null $\forall t<0$) at $iqs = 0$.

In particular, it is interesting to study the effect on *vqs* of the step transition of *ids(t)*.

In order to point out how the present measuring procedure can be repeated after a short time without necessarily starting from zero-state, we will in practice analyse a double step transition of *ids (t)*.

We will apply a first step by going from zero to value *Idc0* at time $t0=0$; afterwards, we will move towards the final value *Idc1* applied at time $t=t1$. The *ids* transform then becomes:

$$Ids(s)=\frac{Idc0}{s}+\frac{Idc1-Idc0}{s}e^{-st1} \qquad (7)$$

By replacing (7) in transfer function (6) and by antitransforming, the expression in the time domain of the response (*vqs*) to the step transition of *ids* will be obtained:

$$vqs(t)=\begin{cases}0 & \forall t<0\\ \dfrac{Lm^2 Idc0}{RrTr^2}e^{-\frac{t}{Tr}}\,sen\,\omega rt & \forall 0<t<t1\\ \dfrac{Lm^2 Idc0}{RrTr^2}e^{-\frac{t}{Tr}}\,sen\,\omega rt\ + & \\ \qquad +\dfrac{Lm^2(Idc1-Idc0)}{RrTr^2}e^{-\frac{t-t1}{Tr}}\,sen\,\omega r(t-t1) & \forall t>t1\end{cases} \tag{8}$$

The second line of (8) is the initial step response with which *ids* transits from *0* to *Idc0*. The third line of (8) provides the response to the following step with which, at time *t1*, *ids* moves from *Idc0* to *Idc1*.

In both cases, *vqs* reacts with a dampened oscillation at a frequency equal to electric rotor speed (ωr) and enveloped by an exponential with time constant $\tau = Tr$ (FIG. 3).

It can further be seen how the transient following the first step transition of *ids* is already exhausting at time *t1* and the *vqs* response for the following transition from *Idc0* to *2Idc0* resembles the previous one though the starting state it not the initial zero-state any more. It will then be enough to store a fixed value of *ids(t)=Idc0* for a duration corresponding to some rotor time constants (in the example a bit more than two) to restore a new steady-state configuration of the pair *vqs*, φqs that is suitable for a new step transition of *ids*; and this without necessarily passing from the zero-state.

Such initial state, compatible with the application of the present process, can be generalised in the one for which *vqs* is simply zeroed (while flux φqs can assume any value, not necessarily null) and it is easy to check that it is restored as steady-state solution of every previous step transition of *ids*. Relationship (8) can further be simplified by approximating the *Lm/Lr* ratio to unit:

$$vqs(t) \cong \begin{cases} 0 & \forall t < 0 \\ RrIdc0\, e^{-\frac{t}{Tr}} sen\,\omega rt & \forall 0 < t < t1 \\ RrIdc0\, e^{-\frac{t}{Tr}r} sen\,\omega rt + Rr(idc1 - Idc0)\, e^{-\frac{t-t1}{Tr}} sen\,\omega r(t-t1) & \forall t > t1 \end{cases} \tag{9}$$

Relationship (9) points out the extreme readability of response (*vqs*) to the step transition of *ids*. In particular:

- the starting width of *vqs* envelope ($Rr\Delta Idc$) does not depend (or depends very little) on speed (ωr), on slip ($\omega slip$), on machine saturation level (namely on magnetic flux Φ).

- the starting width of *vqs* envelope ($Rr\Delta Idc$) depends only on the discontinuity amount on *ids* and on rotor resistance.

It follows that the potential width of the useful signal does not change with operating motor conditions. Only at low speed, the meaningful *vqs* lobes will reach their maximum when the exponential envelope will already be degraded. Speeds can therefore be measured starting from an order of magnitude comparable with the rotor time constant inverse ($1/2\pi Tr$ = few hertz) and over.

Moreover, it can be seen from (9) that, if speed direction is reversed, also the first *vqs* lobe of the step response has an inverted sign (FIG. 4).

From the *vqs* signal analysis, effect of the step modification of *ids*, the electric rotor speed measure (with sign) can be obtained as inverse of period T of the sinusoid enveloped by the exponential ($\omega r = 2\pi/T$). See FIG. 3, FIG. 4, FIG. 5.

The described analysis, referring to a two-phase model, must be generalised by examining four of its aspects in more detail:

- The first current level (*Idc0*) can be interpreted as the one corresponding to the stationing phasor proper that afterwards is made temporarily transit towards a different width (*Idc1*) to induce effects documented on *vqs*. It is as well obvious that also the new current level (as a not necessarily undesired consequence) will produce its own stationing torque value.

- The same results can be immediately applied to a three-phase motor (applying the Clark transform (3.1)). In this context the transition effect on the stationing current will have to be monitored on the triangle linked voltage *vqs* = *vbc* = *vbs-vcs* (FIG. 1).

- If it is still not clear, the step modification of the stationing current *ids* must be meant as instantaneous transition between two different levels of any direct current; the transition from one direct current level to zero is only its more intuitive particular case. The width of the step transition establishes the amount of the effect produced on *vqs*.

- A simplified approach has been proposed that identifies the stationing and stimulus current with *ids* = *ias* and the effects with the behaviour of *vqs* = *vb* - *vc* (FIG. 1). It will be justified how this is not a limit to generality. Let us see it.

The scalar components of the two-phase representation, that so far have been identified with the electric quantities values in motor phases, in a wider interpretation represent the projections of space phasors produced by the motor on any two-phase reference system and whose axes are not necessarily overlapped to stator phase orientations.

Therefore, axis *d* can always be identified with the stationing phasor orientation and axis *q* with the direction in quadrature thereto whichever they

are (namely, the configuration in FIG. 1 with $ids=ias=Idc$ and $iqs=0$ is only a particular, not a constraining choice for orienting the stationing phasor).

This and other results will more easily be understood from the following description of a preferred, but not exclusive embodiment, shown merely as a non-limiting example in the text that follows.

The above described measuring process has been really implemented on a three-phase induction motor with $Pn=1250W$ $p=2$ *poles pair* $Vphase=16V$ corner frequency $fc=75Hz$ $Tr=63msec$. Using a microprocessor power inverter, a stationing current of $Idc=100A$ has been injected in the configuration described in Fig. 1 (Idc entering in a and $Idc/2$ going out of b and c). The motor rotor has been forced to move at a known speed $\omega r = -100rd/sec$.

The sudden stationing current interruption stimulates in the motor, according to the above described theory, a concatenated voltage $vqs=vb-vc$ shown in FIG. 6. The periodicity measure of this voltage, following the step application, provides the searched speed information. The first lobe (main lobe) sign after the ids transition to 0 provides the speed sign.

The modes for determining the vqs period and the main lobe sign can be several. In the current embodiment, and merely as a non-limiting example, the following measuring dynamics has been chosen.

A quick processing unit (microcontroller) checks the injection level of the stationing current (Idc) and takes care of suddenly interrupting the current by opening the inverter half bridges. This operation approximates in a simple way a step transition of a stationing phasor. The sudden opening of power devices implies a very short transient in which the stator currents, sustained only by stator leakage inductances ($Ls-Lm$), discharge their energy, through inverter freewheeling diodes, on the supply line (in this case a 24V battery).

Immediately after the stator currents reset, at a *125μs* interrupt, $vqs=vb-vc$ is read. Every reading is numbered with an increasing index and its absolute value is compared with the relative maximum previously determined, having the same sign. The width of the greater of the two compared elements (current sample and previous relative maximum) and the related index are stored in a continuous search for the absolute maximum. The same process is applied both to the search for a maximum for positive lobes and to the search for a maximum of negative lobes of *vqs*.

Reasonably, the process will end after a survey time that will have, as order of magnitude, the rotor time constant (*Tr*). After that, a stationing phasor can again be applied and it could be, for example, the same phasor preceding the measure or the same phasor used for measuring, waiting that the analysis result on *vqs* allows deciding about the adequacy and usefulness of the stationing phasor itself.

After the survey transient for the step response of *vqs* elapses, a positive maximum will have been stored with its succession number (*index_p*) together with a negative maximum with its succession number (*index_n*). The sinusoid period on *vqs* will then be computed as:

$$T=2\ abs(index\_p-index\_n)\ 125\mu s \qquad (10)$$

from which:

$$abs(\omega r)=2\pi/T$$

Moreover, if:

$$index\_p<index\_n \Rightarrow \omega r<0$$

Instead, if:

$$index\_p>index\_n \Rightarrow \omega r>0$$

After having computed ωr with related sign, it is decided whether the stationing current is enough or not. If the stationing current is enough (ωr close to 0), its proportional reduction can be carried out, at the same time performing further speed monitoring operations and till the final deletion of the current itself.

If, instead, the ωr measure detects a moving motor, a control recovery procedure will have to be carried out. Also for the recovery procedure, merely as a non-limiting information, an execution mode is provided.

After having measured the motor descent speed, the processing unit in a quick ramp will increase the frequency from zero to the value with sign of the detected speed (control re-tuning).

This frequency ramp can be carried out, for example, with a fixed width of the stator current. Once having tuned the frequency on the measured speed, the Sensorless control, that is able to control the motor at a non-zero frequency (line control), will be reactivated. The frequency will then be decreased at very low (not null) values to accompany the motor at very slow speed along the descent with line control and till a new travel request or until the torque produced in line is converted from braking torque to motive torque. (The torque estimating methods in an induction motor are known in literature.) This torque sign transition from braking torque to motive torque testifies that the descent is ended. Then, the frequency will be reduced to zero by applying the stationing current and restarting the timed monitoring procedure.

From what has been stated, the described process can be applied to a more general system re-tuning context (namely the application of a frequency that is next to the electric motor speed once known) every time a control loss occurs. A situation with a lack in the stationing torque along a descent is only a

particular case of control loss. More generally, every time and for any reason the system goes to work with an inadequate slip (i.e. too high: for example due to a sudden deceleration due to an obstacle along the trajectory or following a start-up with running motor) with following motion torque collapse, the on line recovery procedure can be activated and exploits the herein described speed measuring and recovering process. A direct current phasor will be applied, then will be made step-transit towards a different value and the effects on stator voltages will be analysed.

Finally, it must be underlined that the above-described control recovery modes, must be deemed merely as a non-limiting example and the recognition criteria for a control loss status are outside the current scope but are known or can be easily determined if the applied frequency is not null.